In cooperation with the
MASSACHUSETTS DEPARTMENT OF
ENVIRONMENTAL MANAGEMENT

Preliminary Assessment of Streamflow Requirements for Habitat Protection for Selected Sites on the Assabet and Charles Rivers, Eastern Massachusetts

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Cover photo:
Looking downstream, Mine Brook near Franklin,
Massachusetts

Photo by G.W. Parker

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By GENE W. PARKER and DAVID S. ARMSTRONG

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Northborough, Massachusetts
2001

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CONVERSION FACTORS

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile ($ft^3/s/mi^2$)	0.01093	cubic meter per second per square kilometer ($m^3/s/km^2$)
foot (ft)	0.3048	meter (m)
foot per second (ft/s)	0.3048	meter per second (m/s)
mile (mi)	1.609	kilometer (km)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259	hectare
square mile (mi^2)	2.590	square kilometer (km^2)

VERTICAL DATUM

Datum: Local datums used in this report were arbitrarily set at the time of the fieldwork and are not referenced to any National Geodetic Vertical Datum.

Preliminary Assessment of Streamflow Requirements for Habitat Protection for Selected Sites on the Assabet and Charles Rivers, Eastern Massachusetts

By Gene W. Parker *and* David S. Armstrong

Abstract

Streamflow requirements for habitat protection were determined at several critical riffle reaches in the Assabet River and Charles River Basins. The R2Cross and Wetted-Perimeter methods yielded median streamflow requirements of 0.75 cubic feet per second per square mile ($ft^3/s/mi^2$) and 0.13 $ft^3/s/mi^2$, respectively. Three study reaches are on tributaries to the Assabet River (Danforth Brook, Great Brook, and Elizabeth Brook), two are on the mainstem of the Charles River, and one is on a tributary to the Charles River (Mine Brook). The strength of the R2Cross and Wetted-Perimeter methods is that they may be applied at ungaged locations.

A Range of Variability Approach analysis was conducted on a common 30-year period of record from 1969 to 1998 for five mostly unaltered flow, streamgaging stations. The discharge range defined by the median R2Cross and Wetted-Perimeter streamflow requirements brackets the interquartile range for the median of monthly-mean flows during the summer low-flow period, as defined by the Range of Variability Approach analysis of five streamgaging stations. The median R2Cross streamflow requirement for the five riffles compares very closely to the median Tennant 40-percent of the mean annual flow requirement for good habitat condition. The median Wetted-Perimeter streamflow requirement compares closely to the median Tennant 10-percent of the mean annual-flow requirement for a poor habitat condition. Tennant and Range of Variability Approach methods require continuous discharge records for analysis.

INTRODUCTION

During the summer, when water levels are naturally low and the demand for water is high, water users are in competition for a limited supply of water. Federal, State, local agencies, and private citizens' groups are concerned that streamflows altered by water withdrawals and returns could reduce the quality and quantity of the habitat that supports the biological integrity of the Assabet River and Charles River systems.

It is generally recognized that the quantity and quality of water may not be sufficient to meet all needs and interests, and that any solutions to competing water needs and interests will require cooperation among many stakeholders. The Massachusetts Department of Environmental Management (MADEM) determined that the Assabet River and Charles River Basins could serve as pilot areas in which to test methods for determining streamflow requirements for habitat protection. The proposal development and funding requests were presented through work plans of the Concord River Watershed and Charles River Watershed Teams for the Massachusetts Executive Office of Environmental Affairs (EOEA) Watershed Initiative program. The U.S. Geological Survey (USGS), in cooperation with the EOEA Watershed Initiative program and MADEM, began a habitat assessment in 2001 to determine the streamflow requirements in the Assabet and Charles River Basins. An additional goal of the USGS is to coordinate the habitat project with a ground-water modeling project for the Assabet River Basin also being conducted in cooperation with MADEM. The results of the modeling project will help to quantify effects of water-use practices on streamflow and habitat.

Purpose and Scope

This report provides preliminary estimates of streamflow necessary to maintain aquatic habitat in the Assabet and Charles Rivers. The study area includes a reach of the mainstem Charles River and reaches on tributaries to the Assabet and Charles Rivers in Massachusetts. The report describes streamflow requirements determined by means of the R2Cross and Wetted-Perimeter methods. Water-surface-profile models were developed and calibrated from channel surveys and discharge measurements made in the summer and fall of 2001. Hydraulic models were calibrated at six sites—two sites on the mainstem Charles River, and one site each on Mine Brook in the Charles River Basin and Elizabeth Brook, Danforth Brook, and Great Brook in the Assabet River Basin. Streamflow requirements for habitat protection were determined at five riffle sites—two riffle sites on the mainstem Charles River, and one site each on Mine Brook in the Charles River Basin and Elizabeth Brook, and Danforth Brook in the Assabet River Basin.

Description of Study Area

The Assabet River and Charles River are in adjacent drainage basins in Eastern Massachusetts (fig. 1). The Assabet River study sites are in Middlesex County and Worcester County. The Charles River study sites are in Norfolk County. The Assabet River is a subbasin of the Concord River and is bounded by the Nashua River and Blackstone River Basins to the west, the Sudbury River Basin to the East, and Charles River Basin to the south. The Charles River drains into Boston Harbor and is bounded by the Blackstone River Basin to the west, the Sudbury River and Assabet River Basins to the north, and Taunton River and Neponset River Basins to the south.

The three Assabet River study sites are located on riffles on Elizabeth Brook, Great Brook, and Danforth Brook (table 1). The Elizabeth Brook study site is just downstream of a ford on an unnamed road in Stow, MA, and about 0.72 mi upstream of the brook's mouth into the Assabet River. The Great Brook study site is located 1.3 mi east of I-495 near Bolton, MA, and about 1.85 mi upstream of the brook's mouth into Dudley Pond, which is in the Elizabeth Brook Subbasin. The Danforth Brook study site is in Hudson, MA, about 1.35 mi upstream of the brook's mouth into the Assabet River.

The two Charles River study sites are at two riffles on the mainstem upstream of the Walker Street Bridge and the gage at Charles River at Medway (01103200). The Mine Brook study site is at a riffle about 800 ft east of the intersection of Routes 140 and I-495 in Franklin, MA (table 1).

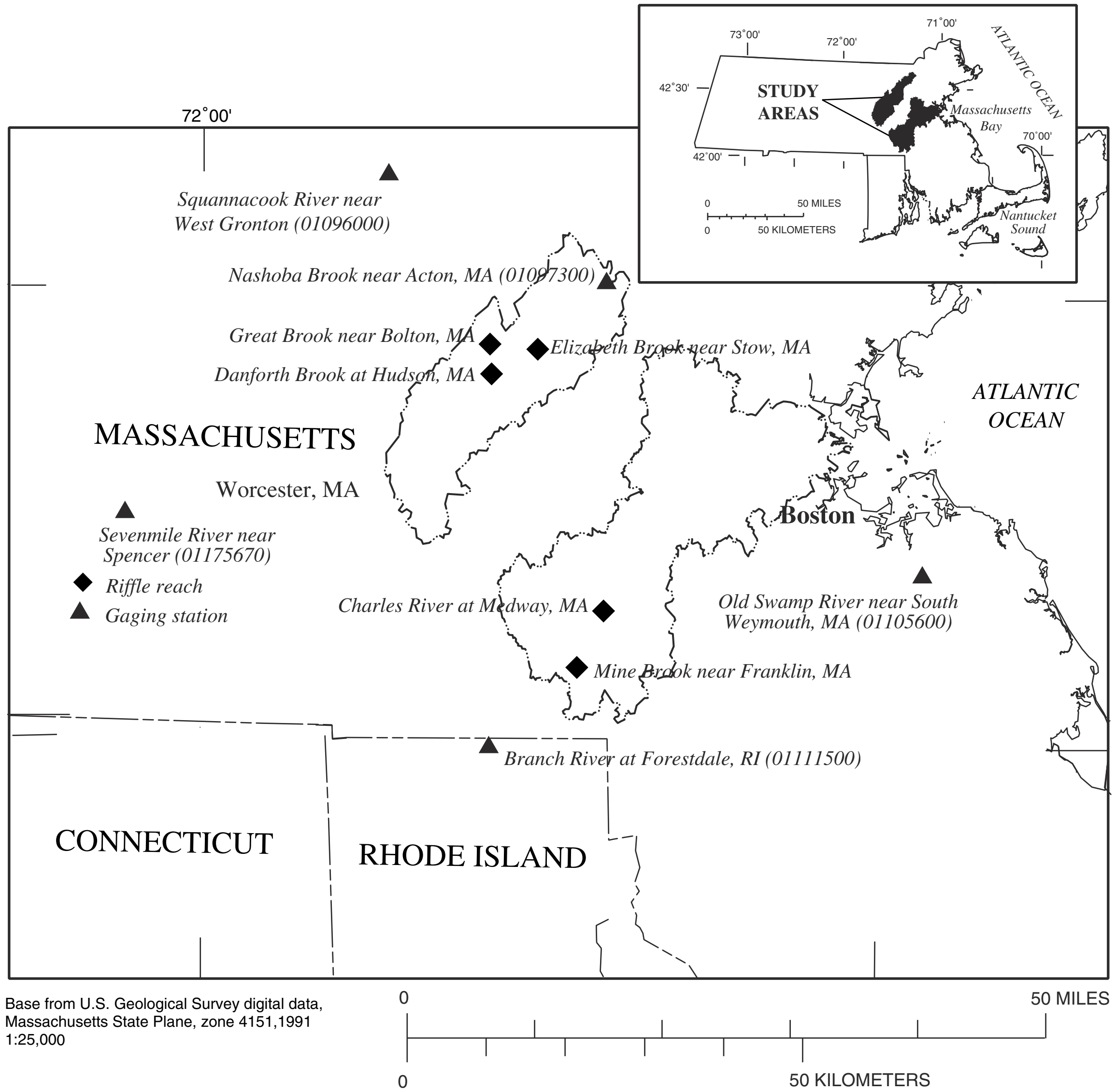

Figure 1. Location of habitat-assessment riffle reaches in and five streamgaging stations near the Assabet River and Charles River Basins, Massachusetts.

Table 1. Location and characteristics of riffle reaches, Assabet and Charles River, Massachusetts

[ft, foot; mi^2, square mile]

River basin	Stream name	Town	Riffle location	Approximate riffle length (ft)	Drainage area (mi^2)
Assabet River...............	Danforth Brook	Hudson	300 ft upstream of Route 85 culvert	80	5.12
	Great Brook	Bolton	Just downstream of Route 117 culvert	80	4.47
	Elizabeth Brook	Stow	0.2 mi south of White Pond Road	70	18.7
Charles River	Mine Brook	Franklin	680 ft upstream of Route 140 culvert	87	10.0
	Charles River	Medway	1480 ft upstream of Walker Street Bridge	30	65.7
	Charles River	Medway	600 ft upstream of Walker Street Bridge	110	65.7

Acknowledgments

The authors are grateful to Sue Beede and Sue Flint from the Organization of the Assabet River, and to Anna Eleria and Dudley Bonsal from the Charles River Watershed Association, who provided assistance with field surveys and surface-water data collection during this study. The cooperation of public and private landowners, who granted access to the Assabet and Charles River riffle study sites, is also appreciated.

METHODS FOR DETERMINING STREAMFLOW REQUIREMENTS FOR HABITAT PROTECTION

The preliminary results of this study include determinations of streamflow requirements for habitat protection at critical riffle sites. Two standard-setting methods were used. These methods are the R2Cross method (Espegren, 1996, 1998; Nehring, 1979) and the Wetted-Perimeter method (Nelson, 1984; Leathe and Nelson, 1986).

The R2Cross and Wetted-Perimeter methods require site-specific physical and hydraulic data at a riffle section, such as channel geometry, average velocity, and mean depth over a range of discharges. An advantage of the R2Cross and Wetted-Perimeter methods is that they are based upon field observations and do not require data from a streamgaging station, so the streamflow requirements obtained by these methods can be applied in hydrologically disturbed drainage basins and at gaged or ungaged sites.

Care must be taken, however, to choose sites that are representative of natural riffle conditions. A riffle is a section of channel, usually between pools, that has a gravel to cobble bed material. The water surface is turbulent with little or no whitewater having average water velocities in the range of 0.6 ft/s to 1.6 ft/s (Bain and Stevenson, 1999). Appropriate riffles for application of the R2Cross and Wetted-Perimeter methods extend across the entire channel, are well defined, and maintain hydraulic control over a range of low to moderate flows. Differences in channel geometry among riffles can create variability in resulting streamflow requirements. For example, reaches that have large boulders or woody debris in the channel that lengthen the flow path or altered streambeds or banks that narrow or widen a natural channel should be avoided. Alterations to channels can have a direct effect on the streamflow recommendations. The artificial widening or narrowing of stream channels can affect wetted perimeter, mean velocity, and mean depth values at a site. The reinforcement of stream banks and streambeds with riprap prevents natural width and depth adjustments. Consequently, streamflow requirements determined for natural riffle sites may not be sufficient to protect habitat at sites in a widened channel, and flow requirements estimated at sites with a narrowed channel may not provide sufficient flows for habitat protection in unaltered stream reaches.

R2Cross Method

The R2Cross method requires selection of a critical riffle along a stream and assumes that a discharge chosen to maintain habitat in the riffle is sufficient to maintain habitat for fish in nearby pools and runs for most life stages of fish and aquatic invertebrates (Nehring, 1979). Streamflow requirements for habitat protection in riffles are determined from flows that meet criteria for three hydraulic parameters: mean depth, percent of bankfull wetted perimeter, and average water velocity (table 2). The hydraulic criteria used in the R2Cross method were developed in Colorado to quantify the amount of streamflow required to "preserve the natural environment to a reasonable degree" (Espegren, 1996). The R2Cross method has been found to produce flow recommendations that are similar to those determined by more data intensive techniques such as the Instream-Flow Incremental Methodology (Nehring, 1979; Colorado Water Conservation Board, 2001).

Table 2. R2Cross hydraulic criteria for protection of aquatic habitat

[Source: Espegren, 1996. ft, foot; ft/s, foot per second; ≥, greater than or equal to]

Stream top width (ft)	Mean depth (ft)	Bankfull wetted perimeter (percent)	Mean velocity (ft/s)
1–20	0.2	50	1.0
21–40	0.2–0.4	50	1.0
41–60	0.4–0.6	50–60	1.0
61–100	0.6–1.0	≥70	1.0

To account for seasonal streamflow variability, the R2Cross method establishes different streamflow requirements for the summer and winter seasons. Initial streamflow recommendations in Colorado are based upon the streamflow that meets all three hydraulic criteria during its high-flow period in summer and two of three hydraulic criteria during its low-flow period in winter. In contrast to Colorado, Massachusetts's flows are generally lowest in mid-summer and early fall (July through September). For this study, streamflow recommendations were established at flows that meet all three R2Cross hydraulic criteria. Streams in Massachusetts have additional stresses during the summer months that are linked to low streamflows, such as high stream temperatures and low dissolved-oxygen concentrations. Meeting all three R2Cross hydraulic criteria will result in more conservative streamflow requirements (Annear and Conder, 1984).

Wetted-Perimeter Method

The Wetted-Perimeter method assumes that there is a direct relation between the wetted perimeter in a riffle and fish habitat in streams (Annear and Conder, 1984; Lohr, 1993). The wetted perimeter of a stream, defined as the width of the streambed and stream banks in contact with water for an individual cross section, is used as a measure of the availability of aquatic habitat over a range of discharges (Annear and Conder, 1984; Nelson, 1984). The Wetted-Perimeter method is based on a plot of the relation between wetted perimeter and discharge (fig. 2). The point of maximum curvature in

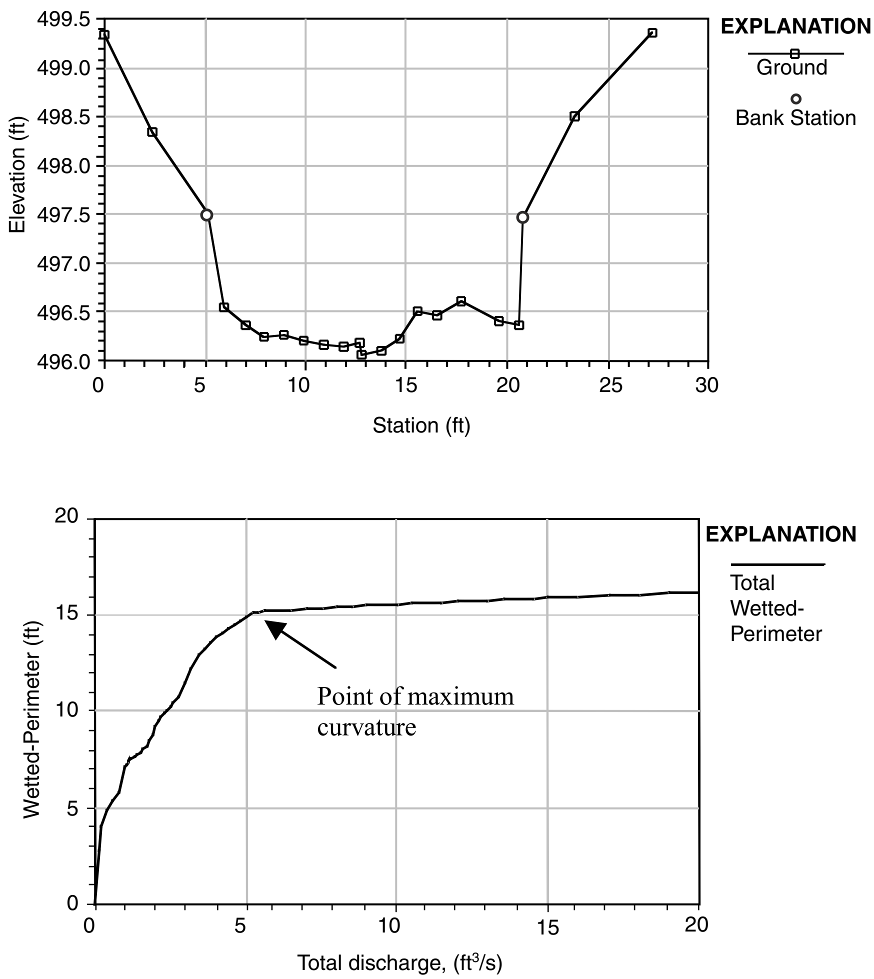

Figure 2. (*A*) Stream channel for cross section 173.65 and (*B*) relation between wetted perimeter and discharge at Mine Brook near Franklin, Massachusetts.

this relation is used to determine the streamflow required for habitat protection. On a stream cross section, this point theoretically corresponds to the break in slope at the bottom of a stream bank where the water surface would begin to recede in a more horizontal direction from the stream banks when flows are decreasing, or to rise up the banks when flows increase. On plots of wetted perimeter versus discharge, the breaks in slope on such graphs are most distinct in riffle channels with rectangular or trapezoidal cross sections. In these cases, water levels that rise above the bottom of the bank cause smaller rates of increase in wetted perimeter for each unit increase of discharge; water levels that fall below the bottom of the bank cause larger rates of decrease in wetted perimeter for each unit decrease in discharge.

Stream-channel geometry varies considerably, and the effectiveness of the Wetted-Perimeter method can be highly dependent upon the cross sections selected in the field. In practice, there is seldom a single break in slope in the wetted-perimeter-to-discharge relation. Many conditions contribute to multiple breaks in slope or the lack of a distinct breakpoint. Multiple breakpoints can correspond to water rising over different features of the channel such as bars or boulders or an irregular channel bed or banks. Less-well-defined breakpoints also may be a function of the number, density, and location of points surveyed along a cross section. For this study, several detailed cross sections were surveyed at each riffle site. Care was taken to survey points along the cross section that corresponded to changes in slope of the streambeds and banks. The elevations of the bottoms of the stream banks that corresponded to a fully wetted channel were identified during surveying. These elevations were used to aid in determination of streamflow requirements for cross sections with no clearly discernible breakpoints or with multiple breakpoints in the wetted-perimeter-to-discharge relation.

Water-Surface-Profile Modeling

A water-surface-profile model, the U.S. Army Corps of Engineers, Hydrologic Engineering Center's River Analysis System (HEC-RAS; Brunner, 2001), was used in this study to simulate the water-surface profile for each riffle site and to determine the hydraulic parameters required for application of both the R2Cross and Wetted-Perimeter methods. HEC-RAS is designed to perform one-dimensional hydraulic calculations for a network of natural or constructed channels under steady or gradually varying flow. The computational procedure is based on the solution of the one-dimensional energy equation from one stream section to the next. Energy losses are evaluated by friction (Manning's equation) and contraction or expansion (coefficient multiplied by the change in velocity head) (Brunner, 2001). Once calibrated, HEC-RAS results were summarized in a table of stage, estimating average depth, average velocity, and percent bankfull wetted perimeter for a range of discharges.

PRELIMINARY STREAMFLOW REQUIREMENTS FOR HABITAT PROTECTION

The R2Cross and Wetted-Perimeter standard-setting methods were used to obtain preliminary streamflow requirements for habitat protection for sites on the Assabet River and Charles River for the summer period. Six riffle reaches were identified as being critical areas for determination of streamflow requirements. Three of these sites are on tributaries to the Assabet River, two are on the mainstem of the Charles River, and one is on a tributary to the Charles River. The results of the analyses are considered preliminary, because the flow conditions that were observed for model calibration were generally low due to the dry weather prior to December 2001.

Danforth Brook at Hudson

The riffle section studied on Danforth Brook is about 300 ft upstream from the Route 85 culvert in a conservation area owned by the town of Hudson (fig. 3). Seven cross sections were surveyed in this study reach, six of which were included in the water surface profile model. The cross sections were along an 80-ft length of pool and riffle habitats and were predominantly trapezoidal in shape. The channel takes a shallow bend to the left along the study reach. There are scattered trees and shrubs along both banks, the bed material is primarily cobbles, and the bank material is a mixture of organic silt, sand, and cobbles. The stream

Figure 3. Danforth Brook at Hudson, Massachusetts, looking upstream.

has a moderately steep slope. The water surface drops about 1.10 ft along the study reach at measured flows of both 0.005 ft^3/s and 0.145 ft^3/s.

The HEC-RAS model was run as a mixed-flow regime on the basis of the standard-step energy method (table 8, at end of this report). Two discharge measurements and measurements of water surfaces at the surveyed cross sections were taken at the study reach for the purpose of model calibration. The calibration discharges were modeled at normal (sub-critical) depth for the most downstream section and a slope of 0.016494 ft/ft was input as a boundary condition; this slope was calculated from water-surface altitudes at surveyed reference points at the most downstream end of the reach. Bankfull discharge was estimated from the 1.5-year flood for the streamgaging station at Nashoba Brook near Acton (01097300) adjusted for the differences in drainage areas, and by comparison with the altitudes of observed bankfull indicators surveyed at the study site.

Initial roughness coefficients for each cross section were estimated by solution of Manning's equation on the basis of the measured discharges and surveyed cross-sectional areas and slopes. The roughness coefficients for each cross section were varied as required until calculated water-surface altitudes matched measured water-surface altitudes with reasonable accuracy. The variability in the roughness coefficients between river stations (table 8) is due to the variability of the actual flow length as opposed to the straight-line lengths between river stations. The longer path the water takes in flowing around the bed material at different discharges changes the energy slope in the analysis and is compensated for by increasing the roughness coefficients to obtain acceptable model calibration. The calibration accuracy was calculated as the root mean square of the differences between the observed and modeled water-surface altitudes for all cross-sections and measured discharges used in the modeled reach. The calibration accuracy was 0.041 ft over the entire reach for both measured discharges. The HEC-RAS software occasionally indicated the need for more cross sections to reduce velocity head drops between sections. Addition of interpolated cross sections would reduce the number of these messages, but would not significantly affect the water-surface profile.

The R2Cross analysis to determine the required streamflow for habitat protection was based upon the HEC-RAS model results for cross sections at river stations 60.8 and 68.7 (table 3). The cross sections at river

Table 3. Required streamflows for habitat protection determined by means of the R2Cross method

[ft, foot; mi, mile; s, second; --, no data]

River and reach	River station	Drainage area (mi^2)	Discharge ft^3/s	Discharge $ft^3/s/mi^2$	Limiting R2Cross criteria
Danforth Brook at Hudson	60.8	5.12	10.5	2.05	Mean velocity
	68.7	5.12	14.3	2.79	Mean velocity
Great Brook near Bolton	109.75	4.47	--	--	--
	114.57	4.47	--	--	--
Elizabeth Brook near Stow	202.05	18.7	9.2	.49	Mean velocity
	213.57	18.7	12.0	.64	Mean depth
	229.45	18.7	7.4	.40	Mean velocity
	241.46	18.7	15.0	.80	Mean depth
Mine Brook near Franklin	123.60	10.01	6.75	.67	Mean velocity
	164.85	10.01	8.75	.87	Mean velocity
	173.65	10.01	2.4	.24	Mean depth
	187.25	10.01	7.25	.72	Mean velocity
Charles River at Medway downstream	641.1	65.7	57.7	.88	Mean depth
Charles River at Medway upstream	1,481.8	65.7	45.4	.69	Mean depth
	1,498.9	65.7	52.8	.80	Mean depth

stations 60.8 and 68.7 were identified as being the critical sections in the riffle reach as they are upstream of the point where the riffle is above any downstream backwater influence. The R2Cross criteria at station 60.8 were an average depth of 0.21 ft, a wetted perimeter of 10.57 ft, and an average velocity of 1.0 ft/s. These criteria were met or exceeded at a discharge of 10.5 ft^3/s (2.05 $ft^3/s/mi^2$). The R2Cross criteria at station 68.7 were an average depth of 0.23 ft, a wetted perimeter of 11.51 ft, and an average velocity of 1.0 ft/s. These criteria were met or exceeded at a discharge of 14.3 ft^3/s (2.79 $ft^3/s/mi^2$). The limiting R2Cross criteria or last of the three criteria to be met was the mean velocity at both station 60.8 and station 68.7.

A wetted perimeter-discharge relation was determined for cross sections at river stations 60.8 and 68.7 on the basis of the HEC-RAS model simulations for a range of discharges up to bankfull flow. Breaks in the wetted perimeter-discharge relation were used to identify a discharge of about 0.35 ft^3/s (0.07 $ft^3/s/mi^2$), for station 60.8 and a discharge of about 0.08 ft^3/s (0.02 $ft^3/s/mi^2$), for station 68.7 (table 4). At these discharges, the average water depth in both cross sections was estimated to be 0.11 ft.

Great Brook near Bolton

This study site is the first riffle reach downstream of the Route 117 culvert (fig. 4). Five cross sections were surveyed in this reach. The most upstream section and the most downstream section were about 64 ft apart near the ends of the riffle reach. The streambed is primarily sandy silt overlying gravel, and cobbles. The three most downstream cross sections have a roughly trapezoidal shape. The two upstream sections have been modified with a vertical concrete wall for the right bank, but the left bank is of natural material. The stream bank on the left side of the channel is soft sediment and shrub vegetation. This riffle was selected for

Table 4. Required streamflows for habitat protection determined by means of the Wetted-Perimeter method

[ft, foot; mi, mile; s, second; --, no data]

River and reach	River station	Drainage area (mi^2)	Discharge	
			ft^3/s	$ft^3/s/mi^2$
Danforth Brook at Hudson	60.8	5.12	0.35	0.07
	68.7	5.12	.08	.02
Great Brook near Bolton	109.75	4.47	--	--
	114.57	4.47	--	--
Elizabeth Brook near Stow	202.05	18.7	1.7	.09
	213.57	18.7	6.0	.32
	229.45	18.7	1.5	.08
	241.46	18.7	3.4	.18
Mine Brook near Franklin	123.60	10.01	2.4	.24
	164.85	10.01	4.0	.40
	173.65	10.01	5.2	.52
	187.25	10.01	1.0	.10
Charles River at Medway downstream	641.1	65.7	8.7	.13
Charles River at Medway upstream......	1,481.8	65.7	1.8	.03
	1,498.9	65.7	3.4	.05

study during a period of very low streamflow. However, the riffle becomes a run at moderate flows and its gradient may be below the recommended limits for the application of Manning's equation. The results of the HEC-RAS model simulations (table 9, at the end of this report) indicate that the surveyed sections at this site are subject to backwater conditions during low to moderate flows and are not appropriate for application of the R2Cross method.

The roughness coefficients for each cross section were varied as required until calculated water-surface altitudes matched measured water-surface altitudes with reasonable accuracy. The calibration accuracy was 0.04 ft over the entire modeled reach for all the measured discharges. The computed water surfaces for the three farthest upstream cross-sections have the same water-surface altitude within 0.02 ft for the calibration discharges, indicating that the sections are in backwater. The R2Cross and Wetted Perimeter analyses were not conducted at this site because riffle conditions are present only during extreme low flows. The site's habitat becomes a run during the range of flows near the streamflow requirements.

Elizabeth Brook near Stow

The riffle section studied on Elizabeth Brook is just downstream of a ford about 0.2 mi south of White Pond Road on an unnamed road in Stow (fig. 5). Six cross sections were surveyed in this study reach; all were included in the water-surface-profile model. The cross sections were along a 70-ft length of riffle. The channel bends slightly to the right and is predominantly trapezoidal in shape. There are shrubs along both banks and larger deciduous trees further back from the channel banks. The bed material is primarily gravel and cobbles; bank material is a mixture of organic soil and cobbles. The reach has a moderate slope and the water surface dropped 0.66 ft to 1.01 ft along the study reach at the measured discharges, which ranged from 1.7 ft^3/s to 30 ft^3/s.

The model was run as a subcritical flow regime using the standard, upstream-step energy method (table 10, at the end of this report). Four discharge measurements were made at the study reach for model calibration, ranging from 1.7 ft^3/s to 30 ft^3/s. The calibration discharges are modeled at normal depth at the most downstream modeled section and a slope of 0.019737 ft/ft was input as a boundary condition. This slope was calculated from water-surface altitudes measured at the surveyed reference points at the downstream end of the reach. Bankfull discharge was estimated by a drainage area adjustment for the 1.5-year flood determined for the gage at Nashoba Brook near Acton (01097300) and by comparison with the altitude of observed bankfull indicators surveyed at the study site.

The roughness coefficients for each cross section were varied as required until calculated water-surface altitudes matched measured water-surface altitudes with reasonable accuracy. The calibration accuracy was 0.022 ft over the entire reach for all four measured discharges.

Figure 4. Great Brook near Bolton, Massachusetts, looking upstream.

Figure 5. Elizabeth Brook near Stow, Massachusetts, looking downstream.

The R2Cross analysis was based on the HEC-RAS model results for cross sections at river stations 202.05, 213.57, 229.45, and 241.46 (table 3). The R2Cross criteria for determining streamflow requirements at station 202.05 were an average depth of 0.31 ft, a wetted perimeter of 15.9 ft, and an average velocity of 1.0 ft/s. These criteria were met at a discharge of 9.2 ft^3/s (0.49 $ft^3/s/mi^2$). The R2Cross criteria at station 213.57—an average depth of 0.27 ft, a wetted perimeter of 13.9 ft, and an average velocity of 1.0 ft/s—were met at a discharge of 12.0 ft^3/s (0.64 $ft^3/s/mi^2$). The R2Cross criteria at station 229.45—an average depth of 0.26 ft, a wetted perimeter of 13.3 ft, and an average velocity of 1.0 ft/s—were met at a discharge of 7.4 ft^3/s (0.40 $ft^3/s/mi^2$). Finally, the R2Cross criteria at station 241.46—an average depth of 0.28 ft, a wetted perimeter of 14.5 ft, and an average velocity of 1.0 ft/s—were met at a discharge of 15.0 ft^3/s (0.80 $ft^3/s/mi^2$). The limiting R2Cross criteria were mean velocity at stations 202.05 and 229.45 and mean depth at stations 213.57 and 241.46.

A wetted perimeter-discharge relation was determined for the cross sections at stations 202.05, 213.57, 229.45, and 241.46 on the basis of the HEC-RAS model results (table 4). Breaks in the wetted perimeter-discharge relation were used to identify a discharge of about 1.7 ft^3/s (0.09 $ft^3/s/mi^2$) for station 202.05, 6.0 ft^3/s (0.32 $ft^3/s/mi^2$) for station 213.57, 1.5 ft^3/s (0.08 $ft^3/s/mi^2$) for station 229.45, and about 3.4 ft^3/s (0.18 $ft^3/s/mi^2$) for station 241.46. For these discharges at these four stations, the average water depth ranged from 0.17 to 0.27 ft with an average depth of 0.22 ft.

Mine Brook near Franklin

The riffle section on Mine Brook is about 680 ft upstream of a culvert under Route 140 in the town of Franklin (fig. 6). Seven cross sections were surveyed along an 87-ft length of riffle habitat and all were included in the water-surface-profile model. The predominantly trapezoidal cross sections are in a fairly straight reach of riffle channel. Only a few scattered shrubs and trees line both banks because the reach

Figure 6. Mine Brook near Franklin, Massachusetts, looking downstream.

flows through a forest of large deciduous trees. The bed material is primarily cobbles, and the bank material is a mixture of organic soil and cobbles. The water surface dropped 1.08 to 1.10 ft along the study reach at measured discharges ranging from 2.03 ft^3/s to 2.30 ft^3/s.

The model was run as a subcritical flow regime on the basis of the standard, upstream-step energy method (table 11, at the end of this report). Two discharge measurements of 2.03 ft^3/s and 2.30 ft^3/s were made for model calibration. The calibration discharges are modeled at normal depth for the most downstream section, and a slope of 0.015691 ft/ft was input as a boundary condition. The slope was calculated from water-surface altitudes measured at the surveyed reference points below the modeled area. Bankfull discharge was estimated by a drainage-area adjustment for the 1.5-year flood for the gage at Nashoba Brook near Acton (01097300), and by comparison with the altitude of observed bankfull indicators surveyed at the study site.

The roughness coefficients for each cross section were varied as required until calculated water-surface altitudes matched measured water-surface altitudes with reasonable accuracy. The calibration accuracy was 0.035 ft over the entire reach for measured discharges.

The R2Cross analysis was applied on the basis of the HEC-RAS model results for the cross sections at river stations 123.60, 164.85, 173.65, and 187.25 (table 3). The R2Cross criteria for determining streamflow requirements at station 123.60—an average depth of 0.20 ft, a wetted perimeter of 9.57 ft, and an average velocity of 1.0 ft/s—were met at a discharge of 6.75 ft^3/s (0.67 $ft^3/s/mi^2$). The R2Cross criteria at station 164.85—an average depth of 0.20 ft, a wetted perimeter of 8.60 ft, and an average velocity of 1.0 ft/s—were met at a discharge of 8.75 ft^3/s (0.87 $ft^3/s/mi^2$). The R2Cross criteria at station 173.65—an average depth of 0.20 ft, a wetted perimeter of 8.68 ft, and an average velocity of 1.0 ft/s—were met at a discharge of 2.4 ft^3/s (0.24 $ft^3/s/mi^2$). Finally, the R2Cross criteria at station 187.25—an average depth of 0.21 ft, a wetted perimeter of 10.71 ft, and an average velocity of 1.0 ft/s—were met at a discharge of 7.25 ft^3/s (0.72 $ft^3/s/mi^2$). The limiting R2Cross criterion was mean velocity at stations 123.60, 164.85, and 187.25 and mean depth at station 173.65.

A wetted perimeter-discharge relation was determined for cross sections at stations 123.60, 164.85, 173.65, and 187.25 on the basis of the HEC-RAS model results (table 4). Breaks in the wetted perimeter-discharge relation were used to identify a discharge of about 2.4 ft^3/s (0.24 $ft^3/s/mi^2$) for station 123.60, 4.0 ft^3/s (0.40 $ft^3/s/mi^2$) for station 164.85, 5.2 ft^3/s (0.52 $ft^3/s/mi^2$) for station 173.65 (fig. 2), and a discharge of about 1.0 ft^3/s (0.10 $ft^3/s/mi^2$) for station 187.25. For these discharges at the four cross sections, the average water depth ranged from 0.18 to 0.4 ft deep with an average depth of 0.28 ft.

Charles River at Medway

Two riffle sections were studied along a 1,500 ft reach upstream of the gage at Charles River at Medway (01103200). The first riffle is at the upstream end of the reach and the downstream riffle is about 600 ft upstream of the Walker Street Bridge (fig. 7). Of the 11 cross-sections that were surveyed in this study reach, 9 were included in a single water surface profile model spanning the river length from Walker Street Bridge to the upstream riffle with the cross sections at river stations 641.1 and 691.6 at the downstream riffle and at river stations 1466.3, 1481.8, and1498.9 at the upstream riffle. The riffle cross sections are predominantly trapezoidal in shape. The channel takes several shallow bends along the course of the study reach. The vegetation along the southern banks of the reach includes large hemlocks, with deciduous trees, small shrubs, and lawn along the northern side. The bed material is primarily gravel, the bank material is a mixture of organic silt, sand, and cobbles. The surveyed water surface dropped 2.49 ft along the study reach at 8.2 ft^3/s and dropped 2.14 ft at 76.2 ft^3/s.

The model was run as a mixed-flow regime on the basis of the standard-step energy method. Several measurements of water-surface altitude were taken at each cross section for model calibration to observed water surfaces at the Medway gage (table 12, at the end of this report). The discharges determined from the Medway gage-rating table could be used as calibration discharges at each cross section because there are no tributaries in the study reach. The water-surface altitudes at the most downstream section were used as initial boundary conditions for the HEC-RAS model.

Figure 7. Charles River at Medway, Massachusetts, looking downstream. Photo (*A*) is of the upstream riffle and (*B*) is of the downstream riffle study reach.

Bankfull discharge was estimated by a drainage area adjustment for the 1.5-year flood, determined from the records for the gage at Charles River at Dover (01103500) and at Nashoba Brook near Acton (01097300), as well as by comparison with observed altitudes of bankfull indicators surveyed along the study reach.

The roughness coefficients for each cross section were varied as required until calculated water-surface altitudes matched measured water-surface altitudes with reasonable accuracy. The calibration accuracy was 0.097 ft over the entire reach for both measured discharges.

The R2Cross analysis to determine streamflow requirements for habitat protection was based upon the HEC-RAS model results for the cross sections at river station 641.1 in the downstream study riffle and the cross sections at river stations 1481.8 and 1498.9 in the upstream riffle (table 3). The R2Cross criteria at station 641.1—an average depth of 0.61 ft, a wetted perimeter of 49.0 ft, and an average velocity of 1.0 ft/s—were met at a discharge of 57.7 ft^3/s (0.88 $ft^3/s/mi^2$). The R2Cross criteria at station 1481.8—an average depth of 0.53 ft, a wetted perimeter of 30.3 ft, and an average velocity of 1.0 ft/s—were met at a discharge of 45.4 ft^3/s (0.69 $ft^3/s/mi^2$). The R2Cross criteria at station 1498.9—an average depth of 0.58 ft, a wetted perimeter of 35.4 ft, and an average velocity of 1.0 ft/s—were met at a discharge of 52.8 ft^3/s (0.80 $ft^3/s/mi^2$). The limiting R2Cross criterion was mean depth for all three cross sections.

A wetted perimeter-discharge relation was determined for cross sections at stations 641.1, 1481.8, and 1498.9 on the basis of the HEC-RAS model results (table 4). The break in the wetted perimeter-discharge relation was used to identify a discharge of about 8.7 ft^3/s (0.13 $ft^3/s/mi^2$) for station 641.1, a discharge of about 1.8 ft^3/s (0.03 $ft^3/s/mi^2$) for station 1481.8, and a discharge of about 3.4 ft^3/s (0.05 $ft^3/s/mi^2$) for station 1498.9. At these discharges, the average water depth in all three cross sections was estimated to be 0.19 ft.

COMPARISON OF STREAMFLOW REQUIREMENTS AND METHODS

A review of the streamflow requirements (tables 3 and 4) determined at selected cross sections using the R2Cross and Wetted-Perimeter methods (fig. 8) illustrates the variability that can be found within and between these methods of analysis. The range of R2Cross streamflow requirements, normalized for drainage area, shows the range between the 25th and 75th percentile (interquartile range) extends from 0.64 $ft^3/s/mi^2$ to 0.87 $ft^3/s/mi^2$. The streamflow requirements derived from the Wetted Perimeter method have a slightly narrower inter-quartile range than the R2Cross requirements. The interquartile ranges from the two methods (fig. 8) do not overlap, indicating that the two methods identify different streamflow requirements. The Wetted Perimeter streamflow requirement indicate when a discharge fully wets the bottom of the channel bed, whereas the R2Cross streamflow requirement requires that a minimum depth and velocity be maintained as well as a minimum ratio of the wetted perimeter to bankfull wetted parameter.

Table 5 shows the average of the cross-section flow requirements within each of the five riffle reaches. The median and mean R2Cross streamflow

Table 5. Summary of R2Cross and Wetted-Perimeter method streamflow requirements for five riffles sites, Assabet and Charles Rivers, Massachusetts

[ft, foot; mi, mile; s, second]

River and reach	Discharge	
	R2Cross ($ft^3/s/mi^2$)	Wetted perimeter ($ft^3/s/mi^2$)
Danforth Brook at Hudson	2.42	0.05
Elizabeth Brook near Stow	.58	.17
Mine Brook near Franklin	.63	.32
Charles River at Medway downstream	.88	.13
Charles River at Medway upstream	.75	.04
Average	1.05	.14
Median	.75	.13

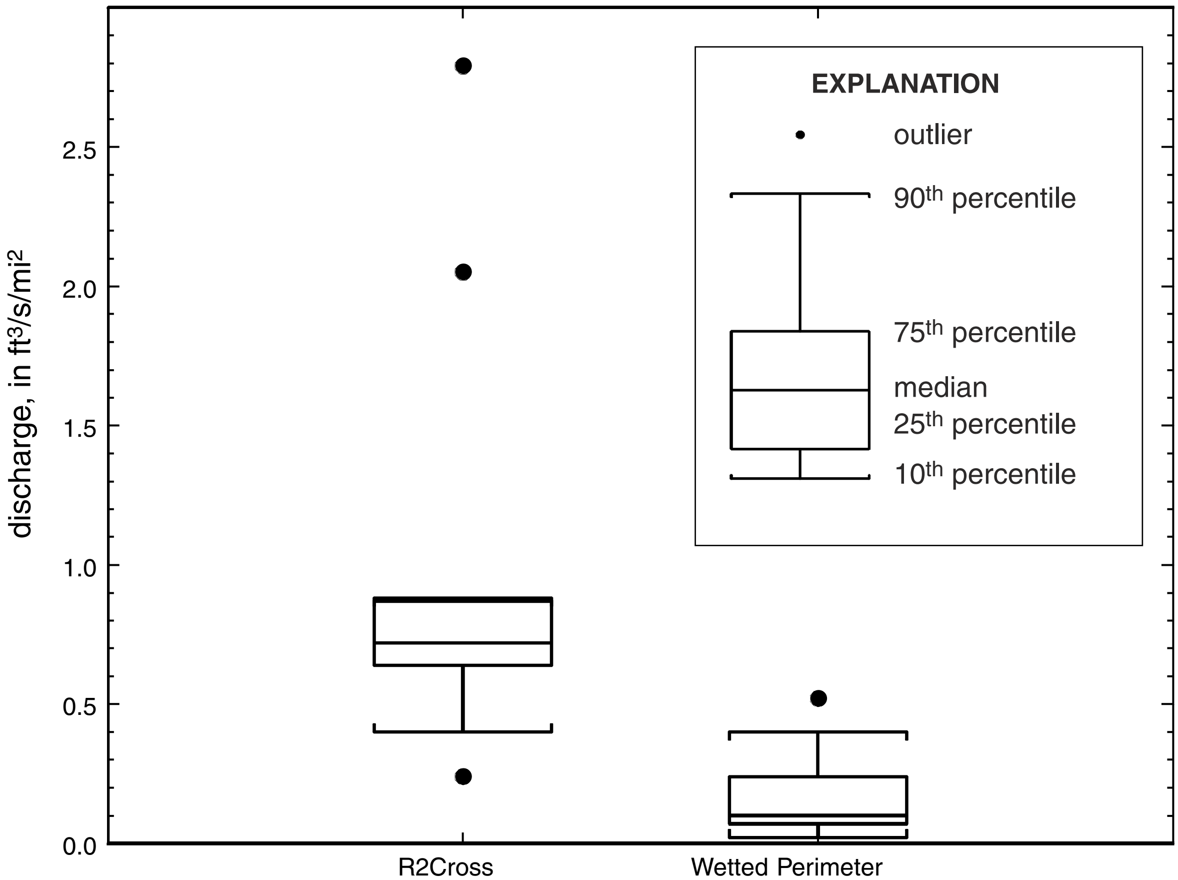

Figure 8. Distribution of streamflow requirements determined by R2Cross and Wetted-Perimeter methods.

requirements for habitat protection were 0.75 $ft^3/s/mi^2$ and 1.05 $ft^3/s/mi^2$, respectively. The median and mean Wetted-Perimeter streamflow requirements were 0.13 $ft^3/s/mi^2$ and 0.14 $ft^3/s/mi^2$, respectively.

A comparison of these median streamflow requirements with observed daily discharges that can be expected during the low-flow summer period at the streamgaging station at Nashoba Brook near Acton (01097300), based on 38 years of record from water year 1963 to water year 2001, is shown in figure 9. The Nashoba Brook is a largely unaltered tributary to the Assabet River; there is only occasional regulation on a small pond in the upper part of the subbasin. The median Wetted-Perimeter streamflow requirement is between the 25^{th}- and 50^{th}-percentile historic daily flows for most of July, August, and September. The median R2Cross streamflow requirement exceeds the 75^{th} percentile for most of the same period. Although comparison of a seasonal streamflow requirement to observed daily discharges at a specific location is interesting, the daily variations in discharges can be influenced by local events and activities that are not indicative of regional conditions.

A diagnostic method and two standard-setting methods (Instream Flow Council, 2002) were applied to streamflow records from 1969 to 1998 for the

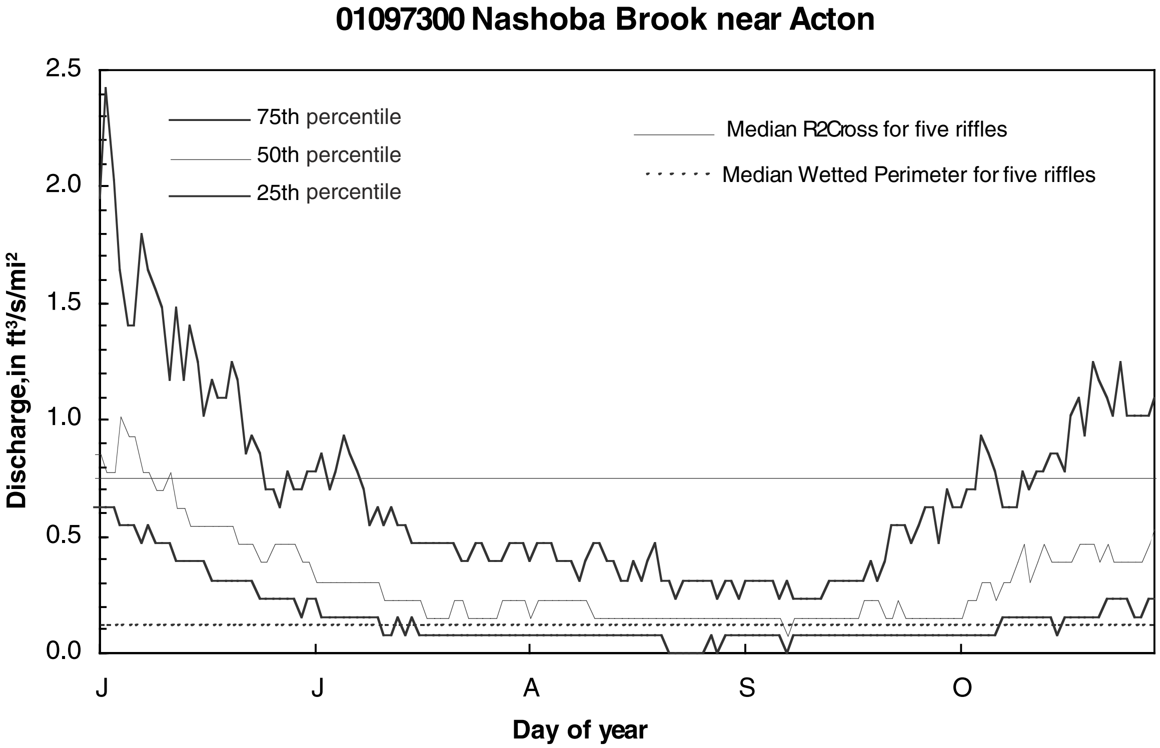

Figure 9. Daily discharge for the streamgaging station at Nashoba Brook near Acton (01097300) for the period 1963 to 2001 compared to median streamflow requirements estimated by the R2Cross and Wetted Perimeter methods, Assabet and Charles Rivers, Massachusetts.

summer low-flow period from five gaging stations with relatively unaltered flow located in or around the Assabet River and Charles River Basins. The diagnostic method is the Range of Variability Approach (RVA) (Richter and others, 1997). The standard setting methods are the Tennant method (Tennant, 1976) and the New England Aquatic Base-Flow (ABF) method (U.S. Fish and Wildlife Service, 1981; Lang, 1999). The five stations chosen for this analysis were the Squannacook River near West Groton, MA (01096000), Nashoba Brook near Acton, MA (01097300), Old Swamp River near South Weymouth, MA (01105600), Branch River at Forestdale, RI (01111500), and Sevenmile River near Spencer, MA (01175670) (fig. 1).

The RVA method defines target streamflows as measured by the interquartile range for each of 33 statistical indicators of hydrologic alteration (IHA) parameters (Richter and others, 1996). Half of these statistics measure the central tendency of the magnitude or rate of change of flow conditions, and half focus on the magnitude, duration, timing, and frequency of extreme events. An example of the results from an IHA analysis is shown in table 6 for the gage at Nashoba Brook near Acton (01097300) for the period of 1969–98. The results of the IHA analyses for all five gages can be viewed at the US Geological Survey Office in Northborough, Massachusetts.

The interquartile ranges of the normalized mean-monthly discharges for the five gages for a common period of record (fig. 10), normalized for drainage area, are mostly bracketed by the R2Cross and Wetted Perimeter median streamflow requirements in the summer low-flow period of July through September. The Wetted Perimeter median requirement is close to the 10th-percentile monthly flow for all five months shown; this relation indicates that the Wetted Perimeter streamflow requirement is violated about 10 percent of the time over the summer months.

Table 6. Indicators of Hydrologic Alteration for the 1969 to 1998 period for the streamgaging station at Nashoba Brook near Acton, Massachusetts (01097300)

[Number in parentheses is discharges per unit basin area, given in cubic foot per second per square mile; ft^3/s, cubic foot per second; $ft^3/s/mi^2$, cubic foot per second per square mile]

Period of condition	Percentile 10th		25th		50th		75th		90th	
Magnitude of month mean discharge, ft^3/s ($ft^3/s/mi^2$)										
October	0.81	(0.06)	2.14	(0.17)	5.12	(0.40)	13.0	(1.01)	24.8	(1.94)
November	3.42	(.27)	7.36	(.58)	15.3	(1.20)	25.6	(2.00)	35.8	(2.80)
December	6.30	(.49)	10.1	(.79)	16.5	(1.29)	35.4	(2.77)	42.9	(3.35)
January	4.61	(.36)	10.5	(.82)	21.0	(1.64)	35.0	(2.73)	55.7	(4.35)
February	12.7	(.99)	16.4	(1.28)	22.4	(1.75)	38.2	(2.98)	53.9	(4.21)
March	20.8	(1.63)	32.2	(2.52)	43.4	(3.39)	52.0	(4.06)	76.7	(5.99)
April	16.2	(1.26)	22.8	(1.78)	41.2	(3.21)	54.6	(4.26)	64.1	(5.01)
May	10.5	(.82)	15.1	(1.18)	23.2	(1.81)	33.1	(2.59)	39.4	(3.08)
June	3.82	(.30)	5.60	(.44)	9.12	(.71)	17.8	(1.39)	42.9	(3.35)
July	1.11	(.09)	1.72	(.13)	4.13	(.32)	8.71	(.68)	14.6	(1.14)
August	.34	(.03)	1.31	(.10)	2.94	(.23)	6.63	(.52)	9.99	(.78)
September	.49	(.04)	1.05	(.08)	2.56	(.20)	6.75	(.53)	10.3	(.81)
Magnitude and duration of annual discharge condition, ft^3/s ($ft^3/s/mi^2$)										
1-day minimum	.08	(.01)	.13	(.01)	.36	(.03)	.97	(.08)	1.43	(.11)
3-day minimum	.09	(.01)	.16	(.01)	.41	(.03)	1.13	(.09)	1.45	(.11)
7-day minimum	.11	(.01)	.24	(.02)	.61	(.05)	1.41	(.11)	1.84	(.14)
30-day minimum	.20	(.02)	.54	(.04)	1.33	(.10)	2.14	(.17)	3.97	(.31)
90-day minimum	.53	(.04)	1.44	(.11)	3.15	(.25)	4.44	(.35)	6.47	(.51)
1-day maximum	76.1	(5.95)	103	(8.05)	174	(13.6)	260	(20.3)	366	(28.6)
3-day maximum	58.5	(4.57)	84.8	(6.63)	144	(11.3)	227	(17.7)	311	(24.3)
7-day maximum	44.4	(3.47)	74.6	(5.83)	110	(8.60)	153	(11.9)	207	(16.2)
30-day maximum	29.8	(2.33)	43.5	(3.40)	63.4	(4.95)	84.3	(6.59)	98.5	(7.70)
90-day maximum	23.8	(1.86)	31.8	(2.49)	44.2	(3.45)	52.5	(4.10)	64.2	(5.02)
7-day minimum/mean annual discharge	.01	(.00)	.01	(.00)	.03	(.00)	.09	(.01)	.11	(.01)
Timing of annual discharge extremes, Julian day										
Date of minimum 1-day discharge	210.7		225.25		249.5		262.75		278.1	
Date of maximum 1-day discharge	26.7		57.25		78.5		97.5		186.8	
Frequency and duration of high and low pulses, number of days										
Days that daily discharge is less than the 25th percentile	4.26		6.79		8.94		18.86		26.45	
Days that daily discharge is greater than the 75th percentile	3.75		4.9		8.63		10.67		14.27	

Table 6. Indicators of Hydrologic Alteration for the 1969 to 1998 period for the streamgaging station at Nashoba Brook near Acton, Massachusetts (01097300)—*Continued*

Period of condition	Percentile				
	10th	25th	50th	75th	90th
Rate and frequency of hydrograph changes, number of days					
Mean of all positive differences between consecutive daily discharges (ft^3/s)	3.24	5.26	8.34	10.81	12.3
Mean of all negative differences between consecutive daily discharges (ft^3/s)	-5.73	-4.9	-4.14	-2.61	-1.69
Zero-discharge days (count)	0	0	0	0	0
Times that daily discharge is less than the 25th percentile daily discharge (count)	2.7	4	7	8	11
Times that daily discharge is greater than the 75th percentile daily discharge (count)	5.4	8	10	13.75	18.3
Times that the trends of the differences between consecutive daily discharges reverse (count)	75.7	83.5	90.5	97.75	103.3

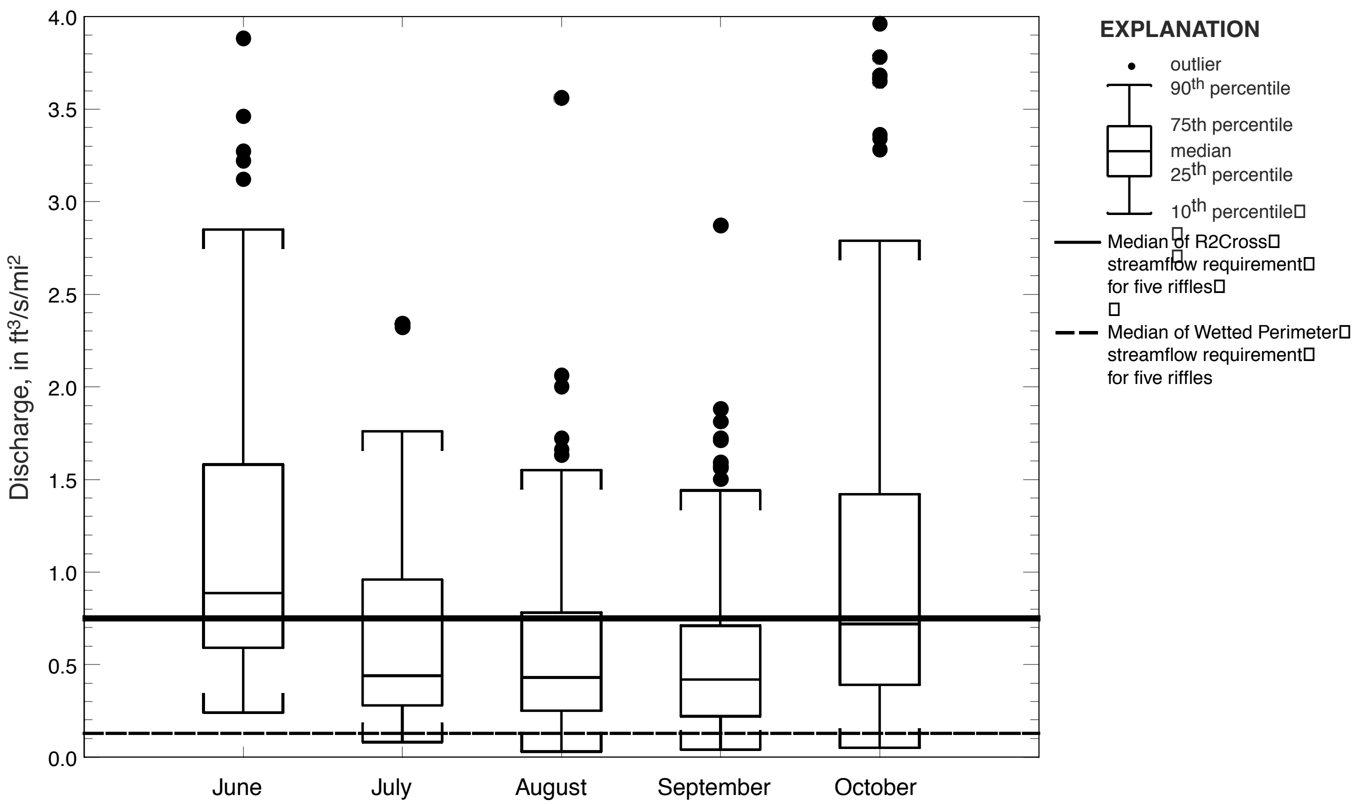

Figure 10. Distribution of mean monthly discharges for the period 1969-1998 for streamgaging stations 01096000, 01097300, 01105600, 01111500, and 01175670 compared with median streamflow requirements estimated by the R2Cross and Wetted-Perimeter methods for five riffles in the Assabet and Charles River Basins, Massachusetts.

Table 7. Median streamflow requirements estimated by the Tennant technique from the combined records of streamgaging stations 01096000, 01097300, 01105600, 01111500, and 01175670

[$ft^3/s/mi^2$, cubic foot per second per square mile]

Standard setting technique	Median streamflow requirement from 5 gages ($ft^3/s/mi^2$)
Tennant—good habitat: (0.4 of the average annual discharge)	0.71
Tennant—fair habitat: (0.3 of the average annual discharge)	.53
Tennant—poor habitat: (0.1 of the average annual discharge)	.18

In the Tennant method (Tennant, 1976), streamflow requirements are based on the observation that aquatic habitat conditions are similar in streams carrying the same proportion of the mean annual flow (Q_{MA}). The Tennant method applies different criteria for winter (October–March) and summer (April–September) flow periods. During summer low-flow periods, minimum streamflows are defined as 40, 30, and 10 percent of the mean annual discharge (Q_{MA}); these streamflows create good, fair, and poor habitat conditions, respectively, according to Tennant (1976). The median results for the five gages (01096000, 01097300, 01105600, 01111500, and 01175670) are presented in table 7. The median R2Cross streamflow requirement for the 5 riffles (0.75 $ft^3/s/mi^2$; table 9) compares closely to the Tennant 0.4 Q_{MA} good-habitat condition requirement (0.71 $ft^3/s/mi^2$). The median Wetted-Perimeter streamflow requirement (0.13 $ft^3/s/mi^2$; table 9) compares closely to the Tennant 0.1 Q_{MA} poor-habitat condition requirement (0.18 $ft^3/s/mi^2$). These results also bracket the RVA monthly interquartile ranges for the summer low-flow period.

SUMMARY AND CONCLUSIONS

During the summer, when streamflows are naturally low and the demand for water is high, water users are in competition for a limited supply of water. This report describes preliminary streamflow requirements necessary to maintain aquatic habitat at six critical riffle sites in the Assabet and Charles Rivers. The report describes summer low-flow-period streamflow requirements determined by the R2Cross and Wetted-Perimeter methods and compares the requirements to a target flow regime recommended by the Range of Variability Approach. The study area includes a main-stem reach of the Charles River and reaches on tributaries to the Assabet and Charles Rivers in Massachusetts. The Assabet River tributary reaches were on Danforth Brook, Great Brook, and Elizabeth Brook. The Charles River Basin reaches were on Mine Brook and on the main stem of the Charles River at Medway.

The R2Cross and Wetted-Perimeter methods require collection of site-specific physical and hydraulic data, such as channel geometry, average velocity, and mean depth at riffle sites. An advantage of the R2Cross and Wetted-Perimeter methods is that they are based on field observations and do not require data from a streamgaging station, so the flow values obtained by these methods can be applied in hydrologically disturbed drainage basins and at gaged or ungaged sites. Care must be taken, however, to choose appropriate study sites. Streamflow requirements determined for natural riffle sites may not be sufficient to protect habitat at sites in a widened channel, and flow requirements estimated at sites with a narrowed channel may not provide sufficient flows for habitat protection in unaltered stream reaches.

A water surface profile model, the U.S. Army Corps of Engineers' River Analysis System (HEC-RAS), was used in this study to simulate the water-surface profile for each riffle site and to determine the hydraulic parameters required for application of both the R2Cross and Wetted-Perimeter methods. HEC-RAS does one-dimensional hydraulic calculations for a network of natural or constructed channels under steady or gradually varying flow. Results from the calibrated HEC-RAS models for a riffle reach were summarized in tables of hydraulic parameters required by the R2Cross and Wetted-Perimeter methods for determining summer low-flow requirements. Of the six reaches modeled, one reach (Great Brook in the Assabet River basin) was affected by backwater at low to moderate discharges and thus could not be considered as a riffle habitat for determining streamflow requirements by means of R2Cross and Wetted-Perimeter methods.

The median flow requirements defined by the R2Cross and Wetted-Perimeter methods for the five-riffle reaches were 0.75 $ft^3/s/mi^2$ and 0.13 $ft^3/s/mi^2$,

respectively. The discharge required for each riffle site was calculated by averaging the streamflow requirements for the appropriate cross sections of each reach.

The median R2Cross and Wetted-Perimeter streamflow requirements for the reaches were compared to observed daily summer-flow records for the streamgaging station at Nashoba Brook near Acton for the (1963 to 2001) period of record. The median R2Cross streamflow requirement is generally greater than the 75th percentile of daily discharges for the July, August, and September as determined from the Nashoba Brook station records. The median R2Cross requirement is generally between the 75th percentile and the median of the daily discharges for June and October. The median Wetted-Perimeter streamflow requirement for the reaches is between the 25th and 50th percentile of historic daily discharges observed at the Nashoba Brook station for the summer low-flow period (July through October). The median Wetted-Perimeter streamflow requirement is usually below the 25th percentile of daily discharge during the month of June for this station.

The RVA diagnostic method was applied to records from five gaging stations with largely unaltered flow in or around the Assabet River and Charles River basins, for the common period of 1969 to 1998 so that regional and seasonal comparisons with the R2Cross and Wetted Perimeter results for the five ungaged riffle reaches could be made. The interquartile ranges of the mean monthly discharges from all five gaging stations, normalized for drainage area, are mostly bracketed by the median R2Cross and Wetted-Perimeter streamflow requirements for July through September. The Wetted-Perimeter median flow requirement is close to the 10th-percentile flow for all five months shown; this result indicates that the Wetted-Perimeter flow requirement is violated about 10 percent of the time.

The Tennant standard-setting method was applied to the records for the same five regional gaging stations used in the RVA analysis. The Tennant method commonly defines minimum streamflows for small streams during summer low-low periods as 40, 30, and 10 percent of the mean annual discharge (Q_{MA}); these flows represent good, fair, and poor habitat conditions, respectively. The median R2cross streamflow requirement for the five riffles compares very closely to the median Tennant 0.4 Q_{MA} definition for good habitat. The median Wetted-Perimeter streamflow requirement compares closely to the median Tennant 0.1 Q_{MA} definition for poor habitat condition requirement. These results correspond well with the R2Cross and Wetted-Perimeter streamflow requirements, which, in turn, bracket the RVA summer-period monthly inter-quartile ranges.

The range of median discharges for the five ungaged riffle reaches defined by the median R2Cross and Wetted Perimeter streamflow requirements—0.75 $ft^3/s/mi^2$ and 0.13 $ft^3/s/mi^2$, respectively—brackets the interquartile range of monthly mean flows for July, August, and September. The interquartile range is the flow management target identified by the RVA record analysis for the five gaging stations that measure mostly unaltered flow. This discharge range is similar to the streamflow requirements determined from the Tennant analysis of the same five gaging stations.

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TABLES 8–12

Table 8. Hydraulic variables simulated by the HEC-RAS model for Danforth Brook at Hudson, Massachusetts

[**River station:** River station numbers increase in an upstream direction. ft^3/s, cubic foot per second; ft, foot; ft/ft, foot per foot; ft^2, square foot; ft/s, foot per second; --, no data]

River station	Discharge (ft^3/s)	Calculated water-surface altitude (ft)	Observed water-surface altitude (ft)	Critical water-surface altitude (ft)	Energy grade slope (ft/ft)	Average velocity (ft/s)	Flow area (ft^2)	Top width (ft)
18.2	0.005	496.49	496.51	496.41	0.016475	0.05	0.10	2.3
18.2	.145	496.71	496.71	496.50	.016479	.10	1.43	10.3
18.2	54.00	497.92	--	497.38	.016494	2.32	23.31	22.2
25.9	.005	496.52	496.59	--	.001949	.05	.11	2.1
25.9	.145	496.73	496.81	--	.001308	.07	1.94	14.5
25.9	54.00	497.96	--	--	.001094	2.20	24.65	20.5
51.9	.005	496.63	496.65	496.57	.023454	.08	.06	1.5
51.9	.145	496.82	496.88	--	.018886	.13	1.12	10.2
51.9	54.00	497.99	--	--	.003493	2.48	21.77	22.2
60.8	.005	497.07	496.10	497.02	.157844	.09	.06	1.6
60.8	.145	497.22	497.27	497.11	.231898	.17	.84	11.5
60.8	54.00	497.98	--	--	.034410	3.63	14.91	20.9
68.7	.005	497.22	497.25	--	.007465	.02	.21	4.3
68.7	.145	497.43	497.45	--	.009904	.06	2.50	16.5
68.7	54.00	498.18	--	--	.009506	3.04	17.75	23.0
81.6	.005	497.29	497.31	--	.003843	.02	.24	7.4
81.6	.145	497.50	497.51	--	.003169	.06	2.55	15.7
81.6	54.00	498.32	--	--	.006165	2.60	20.93	25.1

River station	Discharge (ft^3/s)	Froude No.	Manning's coefficient	Average depth (ft)	Hydraulic radius (ft)	Total wetted perimeter (ft)	Notes
18.2	0.005	0.04	0.494	0.05	0.04	2.32	Measured discharge
18.2	.145	.05	.494	.14	.13	10.68	Measured discharge
18.2	54.00	.40	.083	1.05	.99	23.55	Estimated bankfull discharge
25.9	.005	.04	.194	.05	.05	2.14	Measured discharge
25.9	.145	.04	.187	.13	.13	14.68	Measured discharge
25.9	54.00	.35	.025	1.20	1.15	21.44	Estimated bankfull discharge
51.9	.005	.07	.361	.04	.04	1.49	Measured discharge
51.9	.145	.07	.361	.11	.11	10.22	Measured discharge
51.9	54.00	.44	.035	.98	.97	22.48	Estimated bankfull discharge
60.8	.005	.08	.728	.04	.04	1.59	Measured discharge
60.8	.145	.11	.728	.07	.07	11.49	Measured discharge
60.8	54.00	.75	.061	.71	.70	21.23	Estimated bankfull discharge
68.7	.005	.02	.725	.05	.05	4.29	Measured discharge
68.7	.145	.03	.725	.15	.15	16.56	Measured discharge
68.7	54.00	.61	.040	.77	.76	23.25	Estimated bankfull discharge
81.6	.005	.02	.436	.03	.03	7.37	Measured discharge
81.6	.145	.02	.436	.16	.16	15.83	Measured discharge
81.6	54.00	.50	.040	.83	.81	25.70	Estimated bankfull discharge

Table 9. Hydraulic variables simulated by the HEC-RAS model for Great Brook near Bolton, Massachusetts

[**River station:** River station numbers increase in an upstream direction. ft^3/s, cubic foot per second; ft, foot; ft/ft, foot per foot; ft^2, square foot; ft/s, foot per second; --, no data]

River station	Discharge (ft^3/s)	Calculated water-surface altitude (ft)	Observed water-surface altitude (ft)	Critical water-surface altitude (ft)	Energy grade slope (ft/ft)	Average velocity (ft/s)	Flow area (ft^2)	Top width (ft)
34.95	0.25	498.07	498.12	497.92	0.030702	0.29	0.87	6.2
34.95	.30	498.08	498.08	497.93	.030676	.31	.98	6.3
34.95	.32	498.09	498.09	497.93	.030682	.31	1.02	6.3
34.95	.35	498.10	498.12	497.94	.030692	.32	1.08	6.46
34.95	.78	498.21	498.21	497.99	.030726	.44	1.78	7.0
34.95	1.08	498.24	498.24	498.01	.030722	.53	2.04	7.2
34.95	10.00	498.47	498.58	498.35	.030686	2.62	3.81	9.0
47.93	.25	498.19	498.18	--	.004463	.19	1.31	7.0
47.93	.30	498.21	498.22	--	.004606	.21	1.44	7.1
47.93	.32	498.22	498.23	--	.004641	.21	1.50	7.4
47.93	.35	498.23	498.25	--	.004716	.22	1.60	7.9
47.93	.78	498.34	498.34	--	.005132	.29	2.65	10.4
47.93	1.08	498.39	498.40	--	.005508	.34	3.13	10.6
47.93	10.00	498.63	498.67	--	.003267	1.70	5.90	12.4
90.51	.25	498.19	498.18	--	.000019	.10	2.57	8.2
90.51	.30	498.22	498.24	--	.000065	.11	2.77	8.4
90.51	.32	498.23	498.24	--	.000078	.11	2.85	8.4
90.51	.35	498.24	498.27	--	.000086	.12	2.97	8.6
90.51	.78	498.37	498.38	--	.000239	.18	4.29	11.3
90.51	1.08	498.43	498.44	--	.000340	.22	4.94	11.8
90.51	10.00	498.73	498.71	--	.000985	1.15	8.68	13.1
109.75	.25	498.20	498.23	497.94	.000494	.15	1.71	9.6
109.75	.30	498.22	498.25	497.95	.000438	.15	1.96	9.6
109.75	.32	498.23	498.28	497.95	.000419	.16	2.06	9.7
109.75	.35	498.25	498.27	497.95	.000398	.16	2.20	9.7
109.75	.78	498.38	498.39	498.00	.000373	.22	3.50	10.2
109.75	1.08	498.43	498.45	498.03	.000399	.26	4.09	10.4
109.75	10.00	498.75	498.74	498.34	.001434	1.33	7.52	11.7
114.57	.25	498.20	498.29	498.15	.047276	.55	.45	6.2
114.57	.30	498.23	498.30	498.16	.024331	.47	.63	6.6
114.57	.32	498.24	498.33	498.16	.020127	.45	.71	6.8
114.57	.35	498.25	498.32	498.17	.015827	.43	.81	7.0
114.57	.78	498.38	498.42	498.20	.006636	.45	1.75	7.4
114.57	1.08	498.44	498.48	498.22	.007031	.49	2.19	8.3
114.57	10.00	498.74	498.77	498.54	.047944	1.96	5.11	10.1

Table 9. Hydraulic variables simulated by the HEC-RAS model for Great Brook near Bolton, Massachusetts—*Continued*

River station	Discharge (ft^3/s)	Froude No.	Manning's coefficient	Average depth (ft)	Hydraulic radius (ft)	Total wetted perimeter (ft)	Notes
34.95	0.25	0.14	0.240	0.14	0.14	6.36	Measured discharge
34.95	.30	.14	.240	.16	.15	6.49	Measured discharge
34.95	.32	.14	.240	.16	.16	6.53	Measured discharge
34.95	.35	.14	.240	.17	.16	6.60	Measured discharge
34.95	.78	.15	.230	.26	.24	7.34	Measured discharge
34.95	1.08	.17	.205	.28	.27	7.61	Measured discharge
34.95	10.00	.71	.053	.42	.39	9.68	Measured discharge
47.93	.25	.08	.169	.19	.18	7.12	Measured discharge
47.93	.30	.08	.164	.20	.20	7.24	Measured discharge
47.93	.32	.08	.162	.20	.20	7.52	Measured discharge
47.93	.35	.09	.158	.20	.20	8.05	Measured discharge
47.93	.78	.10	.143	.25	.25	10.66	Measured discharge
47.93	1.08	.11	.139	.29	.29	10.89	Measured discharge
47.93	10.00	.43	.030	.48	.46	12.72	Measured discharge
90.51	.25	.03	.030	.31	.30	8.47	Measured discharge
90.51	.30	.03	.052	.33	.32	8.65	Measured discharge
90.51	.32	.03	.055	.34	.33	8.71	Measured discharge
90.51	.35	.04	.056	.35	.33	8.90	Measured discharge
90.51	.78	.05	.065	.38	.37	11.64	Measured discharge
90.51	1.08	.06	.069	.42	.40	12.20	Measured discharge
90.51	10.00	.25	.030	.66	.64	13.62	Measured discharge
109.75	.25	.06	.070	.18	.17	9.86	Measured discharge
109.75	.30	.06	.069	.20	.20	9.94	Measured discharge
109.75	.32	.06	.068	.21	.21	9.98	Measured discharge
109.75	.35	.06	.068	.23	.22	10.04	Measured discharge
109.75	.78	.07	.061	.34	.33	10.66	Measured discharge
109.75	1.08	.07	.058	.39	.37	10.94	Measured discharge
109.75	10.00	.29	.030	.64	.60	12.58	Measured discharge
114.57	.25	.36	.100	.07	.07	6.36	Measured discharge
114.57	.30	.27	.100	.10	.09	6.87	Measured discharge
114.57	.32	.25	.100	.10	.10	7.06	Measured discharge
114.57	.35	.22	.100	.12	.11	7.25	Measured discharge
114.57	.78	.16	.100	.24	.22	7.83	Measured discharge
114.57	1.08	.17	.100	.26	.25	8.75	Measured discharge
114.57	10.00	.48	.100	.51	.47	10.94	Measured discharge

Table 10. Hydraulic variables simulated by the HEC-RAS model for Elizabeth Brook near Stow, Massachusetts

[**River station:** River station numbers increase in an upstream direction. ft^3/s, cubic foot per second; ft, foot; ft/ft, foot per foot; ft^2, square foot; ft/s, foot per second; --, no data]

River station	Discharge (ft^3/s)	Calculated water-surface altitude (ft)	Observed water-surface altitude (ft)	Critical water-surface altitude (ft)	Energy grade slope (ft/ft)	Average velocity (ft/s)	Flow area (ft^2)	Top width (ft)
174.35	1.70	497.08	497.03	496.81	0.019710	0.30	5.72	23.3
174.35	3.20	497.12	497.09	496.88	.019735	.47	6.83	23.8
174.35	11.00	497.19	497.18	497.02	.019716	1.32	8.36	24.0
174.35	30.00	497.23	497.24	497.20	.019663	3.17	9.47	24.2
174.35	80.00	497.57	--	497.56	.019737	4.44	18.21	30.4
185.68	1.70	497.20	497.20	--	.006956	.35	4.92	22.5
185.68	3.20	497.23	497.23	--	.005484	.57	5.63	23.2
185.68	11.00	497.36	497.38	--	.011713	1.25	8.79	26.5
185.68	30.00	497.47	497.47	--	.012915	2.50	11.99	29.7
185.68	80.00	497.82	--	--	.007950	3.52	22.75	32.0
202.05	1.70	497.37	497.34	--	.020186	.51	3.35	19.0
202.05	3.20	497.41	497.42	--	.030851	.78	4.13	21.2
202.05	11.00	497.53	497.53	--	.011527	1.58	6.96	24.7
202.05	30.00	497.67	497.67	--	.012613	2.87	10.47	28.1
202.05	80.00	497.93	--	497.92	.015294	4.31	18.58	31.4
213.57	1.70	497.51	497.51	--	.006675	.34	5.04	25.2
213.57	3.20	497.55	497.55	--	.005868	.53	6.00	25.6
213.57	11.00	497.65	497.65	--	.006353	1.28	8.57	26.0
213.57	30.00	497.82	497.80	--	.006472	2.29	13.10	26.5
213.57	80.00	498.16	--	--	.007978	3.58	22.34	27.4
229.45	1.70	497.71	497.67	--	.035669	.57	2.97	17.4
229.45	3.20	497.74	497.75	--	.046278	.89	3.60	19.7
229.45	11.00	497.84	497.82	497.78	.046381	1.93	5.69	22.9
229.45	30.00	497.98	497.98	497.97	.059812	3.30	9.08	23.9
229.45	80.00	498.34	--	498.31	.044930	4.41	18.13	26.6
241.46	1.70	497.93	497.69	--	.011605	.35	4.89	24.4
241.46	3.20	498.00	498.00	--	.011315	.49	6.47	24.9
241.46	11.00	498.13	498.13	--	.011699	1.13	9.73	25.6
241.46	30.00	498.26	498.25	--	.006796	2.27	13.23	26.3
241.46	80.00	498.59	--	--	.005136	3.61	22.20	28.6

Table 10. Hydraulic variables simulated by the HEC-RAS model for Elizabeth Brook near Stow, Massachusetts—*Continued*

River station	Discharge (ft^3/s)	Froude No.	Manning's coefficient	Average depth (ft)	Hydraulic radius (ft)	Total wetted perimeter (ft)	Notes
174.35	1.70	0.11	0.274	0.25	0.24	23.44	Measured discharge
174.35	3.20	.15	.193	.29	.29	23.90	Measured discharge
174.35	11.00	.39	.078	.35	.35	24.18	Measured discharge
174.35	30.00	.89	.035	.39	.39	24.38	Measured discharge
174.35	80.00	.97	.035	.60	.59	30.81	Estimated bankfull discharge
185.68	1.70	.13	.130	.22	.22	22.61	Measured discharge
185.68	3.20	.20	.075	.24	.24	23.33	Measured discharge
185.68	11.00	.38	.061	.33	.33	26.69	Measured discharge
185.68	30.00	.69	.037	.40	.40	29.86	Measured discharge
185.68	80.00	.73	.030	.71	.70	32.40	Estimated bankfull discharge
202.05	1.70	.21	.131	.18	.18	19.02	Measured discharge
202.05	3.20	.31	.113	.19	.19	21.33	Measured discharge
202.05	11.00	.52	.043	.28	.28	24.80	Measured discharge
202.05	30.00	.83	.030	.37	.37	28.32	Measured discharge
202.05	80.00	.98	.030	.59	.59	31.74	Estimated bankfull discharge
213.57	1.70	.13	.123	.20	.20	25.32	Measured discharge
213.57	3.20	.19	.081	.23	.23	25.72	Measured discharge
213.57	11.00	.39	.044	.33	.33	26.19	Measured discharge
213.57	30.00	.57	.032	.50	.49	26.81	Measured discharge
213.57	80.00	.70	.032	.81	.80	28.03	Estimated bankfull discharge
229.45	1.70	.24	.150	.17	.17	17.50	Measured discharge
229.45	3.20	.37	.115	.18	.18	19.80	Measured discharge
229.45	11.00	.68	.065	.25	.25	22.97	Measured discharge
229.45	30.00	.95	.057	.38	.38	24.08	Measured discharge
229.45	80.00	.94	.055	.68	.68	26.82	Estimated bankfull discharge
241.46	1.70	.14	.157	.20	.20	24.52	Measured discharge
241.46	3.20	.17	.130	.26	.26	25.03	Measured discharge
241.46	11.00	.32	.074	.38	.38	25.79	Measured discharge
241.46	30.00	.56	.034	.50	.50	26.59	Measured discharge
241.46	80.00	.72	.025	.78	.77	28.94	Estimated bankfull discharge

Table 11. Hydraulic variables simulated by the HEC-RAS model for Mine Brook near Franklin, Massachusetts

[**River station:** River station numbers increase in an upstream direction. ft^3/s, cubic foot per second; ft, foot; ft/ft, foot per foot; ft^2, square foot; ft/s, foot per second; --, no data]

River station	Discharge (ft^3/s)	Calculated water-surface altitude (ft)	Observed water-surface altitude (ft)	Critical water-surface altitude (ft)	Energy grade slope (ft/ft)	Average velocity (ft/s)	Flow area (ft^2)	Top width (ft)
100	2.03	495.89	495.89	495.66	0.015712	0.48	4.24	17.2
100	2.30	495.91	495.95	495.67	.015704	.50	4.60	17.6
100	50.00	496.89	--	496.28	.015691	1.98	25.34	24.2
112.91	2.03	496.02	496.00	--	.006675	.53	3.87	17.2
112.91	2.30	496.04	496.05	--	.006611	.55	4.20	17.6
112.91	50.00	496.98	--	--	.004312	1.96	25.56	25.1
123.60	2.03	496.13	--	--	.019559	.62	3.27	13.6
123.60	2.30	496.15	496.14	--	.020427	.65	3.54	14.3
123.60	50.00	497.05	--	--	.035843	2.67	18.73	18.1
143.62	2.03	496.27	496.23	--	.003305	.48	4.19	13.6
143.62	2.30	496.29	496.28	--	.003388	.51	4.51	13.9
143.62	50.00	497.44	--	--	.010102	2.14	23.34	18.6
164.85	2.03	496.34	496.30	--	.003078	.54	3.76	12.1
164.85	2.30	496.36	496.32	--	.003094	.57	4.07	12.4
164.85	50.00	497.50	--	--	.001836	2.43	20.58	15.5
173.65	2.03	496.40	496.45	--	.082208	1.23	1.65	9.1
173.65	2.30	496.42	496.48	--	.073214	1.22	1.89	9.7
173.65	50.00	497.52	--	--	.016101	2.78	18.01	15.8
187.25	2.03	496.99	496.97	496.77	.025222	.50	4.04	17.6
187.25	2.30	497.00	497.05	496.79	.026171	.54	4.29	17.9
187.25	50.00	497.73	--	--	.014422	2.71	18.46	20.6

Table 11. Hydraulic variables simulated by the HEC-RAS model for Mine Brook near Franklin, Massachusetts—*Continued*

River station	Discharge (ft^3/s)	Froude No.	Manning's coefficient	Average depth (ft)	Hydraulic radius (ft)	Total wetted perimeter (ft)	Notes
100	2.03	0.17	0.150	0.25	0.24	17.70	Measured discharge
100	2.30	.17	.149	.26	.25	18.11	Measured discharge
100	50.00	.33	.096	1.05	.97	26.19	Estimated bankfull discharge
112.91	2.03	.20	.085	.22	.22	17.25	Measured discharge
112.91	2.30	.20	.085	.24	.24	17.68	Measured discharge
112.91	50.00	.34	.051	1.02	1.00	25.54	Estimated bankfull discharge
123.60	2.03	.22	.129	.24	.24	13.69	Measured discharge
123.60	2.30	.23	.129	.25	.25	14.38	Measured discharge
123.60	50.00	.46	.104	1.03	.98	19.14	Estimated bankfull discharge
143.62	2.03	.15	.080	.31	.31	13.69	Measured discharge
143.62	2.30	.16	.080	.33	.32	13.96	Measured discharge
143.62	50.00	.33	.080	1.26	1.20	19.46	Estimated bankfull discharge
164.85	2.03	.17	.069	.31	.30	12.46	Measured discharge
164.85	2.30	.17	.068	.33	.32	12.82	Measured discharge
164.85	50.00	.37	.030	1.33	1.20	17.21	Estimated bankfull discharge
173.65	2.03	.51	.110	.18	.18	9.28	Measured discharge
173.65	2.30	.49	.109	.19	.19	9.91	Measured discharge
173.65	50.00	.46	.070	1.14	1.04	17.35	Estimated bankfull discharge
187.25	2.03	.19	.174	.23	.23	17.92	Measured discharge
187.25	2.30	.19	.172	.24	.24	18.14	Measured discharge
187.25	50.00	.50	.060	.90	.86	21.42	Estimated bankfull discharge

Table 12. Hydraulic variables simulated by the HEC-RAS model for Charles River at Medway, Massachusetts

[**River station:** River station numbers increase in an upstream direction. ft^3/s, cubic foot per second; ft, foot; ft/ft, foot per foot; ft^2, square foot; ft/s, foot per second; --, no data]

River station	Discharge (ft^3/s)	Calculated water-surface altitude (ft)	Observed water-surface altitude (ft)	Critical water-surface altitude (ft)	Energy grade slope (ft/ft)	Average velocity (ft/s)	Flow area (ft^2)	Top width (ft)
100	8.20	787.99	--	787.62	0.000835	0.57	14.35	44.7
100	10.50	788.04	--	787.66	.000905	.63	16.63	47.4
100	12.60	788.09	--	787.70	.001013	.67	18.92	54.1
100	14.20	788.11	--	787.72	.001025	.70	20.27	54.2
100	19.10	788.17	--	787.78	.001135	.81	23.53	54.4
100	76.20	788.54	--	788.12	.002378	1.74	43.72	55.6
100	170.00	788.92	--	788.40	.003259	2.59	65.64	58.8
374.2	8.20	788.19	--	--	.000639	.64	12.73	27.3
374.2	10.50	788.26	--	--	.000704	.72	14.61	28.6
374.2	12.60	788.31	--	--	.000714	.78	16.20	31.1
374.2	14.20	788.34	--	--	.000732	.83	17.09	32.2
374.2	19.10	788.42	--	--	.000691	.98	19.56	33.3
374.2	76.20	788.93	--	--	.000987	1.97	38.61	39.7
374.2	170.00	789.52	--	--	.001585	2.72	62.50	41.3
580.9	8.20	788.25	788.27	--	.000147	.30	27.65	61.4
580.9	10.50	788.32	788.31	--	.000140	.33	31.79	64.8
580.9	12.60	788.37	788.31	--	.000126	.36	35.15	67.0
580.9	14.20	788.40	--	--	.000125	.38	37.03	68.3
580.9	19.10	788.47	788.39	--	.000110	.45	42.51	71.7
580.9	76.20	789.18	789.24	--	.000864	.71	107.41	100.3
580.9	170.00	789.83	--	--	.000671	.98	172.82	101.0
641.1	8.20	788.27	788.49	--	1.006706	1.44	5.71	16.7
641.1	10.50	788.33	788.47	--	1.019691	1.56	6.74	17.6
641.1	12.60	788.37	788.47	--	1.077331	1.67	7.54	18.4
641.1	14.20	788.39	788.41	--	1.195012	1.78	7.98	19.2
641.1	19.10	788.46	788.62	--	1.743136	2.02	9.47	25.2
641.1	76.20	789.29	789.28	--	.009097	1.40	54.49	66.5
641.1	170.00	789.88	--	--	.002477	1.80	94.28	68.7
691.6	8.20	788.90	788.84	788.67	.003210	.67	12.33	54.4
691.6	10.50	788.94	788.92	788.70	.003068	.71	14.81	54.8
691.6	12.60	788.98	788.94	788.71	.002961	.74	17.00	55.2
691.6	14.20	789.01	788.92	788.75	.002965	.78	18.24	55.4
691.6	19.10	789.05	789.00	788.81	.002780	.93	20.55	55.7
691.6	76.20	789.47	--	--	.002122	1.69	45.14	58.6
691.6	170.00	790.02	--	--	.003992	2.19	77.70	61.4
1,284	8.20	789.52	--	789.04	.000506	.36	22.65	43.1
1,284	10.50	789.59	--	789.06	.000549	.41	25.92	44.3
1,284	12.60	789.65	--	789.08	.000589	.44	28.56	45.3
1,284	14.20	789.70	--	789.10	.000605	.46	30.62	46.0
1,284	19.10	789.81	--	789.14	0.000715	0.53	35.86	49.6
1,284	76.20	790.48	790.48	--	.001330	1.06	72.16	56.7
1,284	170.00	791.31	--	--	.001296	1.43	119.29	57.5

Table 12. Hydraulic variables simulated by the HEC-RAS model for Charles River at Medway, Massachusetts—*Continued*

River station	Discharge (ft^3/s)	Calculated water-surface altitude (ft)	Observed water-surface altitude (ft)	Critical water-surface altitude (ft)	Energy grade slope (ft/ft)	Average velocity (ft/s)	Flow area (ft^2)	Top width (ft)
1,466.3	8.20	790.11	790.26	790.11	.034457	2.15	3.81	21.8
1,466.3	10.50	790.13	790.33	790.13	.041208	2.49	4.21	22.1
1,466.3	12.60	790.15	790.40	790.15	.040078	2.64	4.77	22.5
1,466.3	14.20	790.17	790.35	790.17	.038389	2.72	5.23	22.8
1,466.3	19.10	790.23	--	790.23	.036699	2.96	6.45	23.9
1,466.3	76.20	791.01	791.05	--	.013620	2.13	35.84	44.8
1,466.3	170.00	791.74	--	--	.007729	2.45	70.20	49.2
1,481.8	8.20	790.50	790.50	--	.014794	1.05	7.83	30.2
1,481.8	10.50	790.54	790.54	--	.012955	1.16	9.08	31.0
1,481.8	12.60	790.57	790.70	--	.012561	1.27	9.96	32.1
1,481.8	14.20	790.59	790.56	--	.012090	1.34	10.62	33.0
1,481.8	19.10	790.63	--	--	.011709	1.56	12.23	34.9
1,481.8	76.20	791.15	791.19	--	.007573	2.29	33.26	45.3
1,481.8	170.00	791.83	--	--	.005041	2.58	67.15	53.3
1,498.9	8.20	790.76	790.76	790.53	.014895	.76	10.81	34.3
1,498.9	10.50	790.78	790.76	790.56	.013998	.92	11.40	34.8
1,498.9	12.60	790.79	790.84	790.58	.012720	1.06	11.83	35.1
1,498.9	14.20	790.80	790.80	790.61	.011771	1.17	12.10	35.3
1,498.9	19.10	790.84	--	790.65	.011451	1.38	13.80	36.5
1,498.9	76.20	791.33	791.38	790.99	.014464	2.18	35.15	51.1
1,498.9	170.00	791.93	--	791.34	.009299	2.54	68.47	57.9

River station	Discharge (ft^3/s)	Froude No.	Manning's coefficient	Average depth (ft)	Hydraulic radius (ft)	Total wetted perimeter (ft)	Notes
100	8.20	0.18	0.035	0.32	0.32	45.18	Measured discharge
100	10.50	.19	.035	.35	.35	47.85	Measured discharge
100	12.60	.20	.035	.35	.35	54.67	Measured discharge
100	14.20	.20	.035	.37	.37	54.77	Measured discharge
100	19.10	.22	.035	.43	.43	55.00	Measured discharge
100	76.20	.35	.035	.79	.77	56.60	Measured discharge
100	170.00	.43	.035	1.12	1.10	59.91	Estimated bankfull discharge
374.2	8.20	.17	.035	.47	.47	27.37	Measured discharge
374.2	10.50	.18	.035	.51	.51	28.67	Measured discharge
374.2	12.60	.19	.033	.52	.52	31.21	Measured discharge
374.2	14.20	0.20	0.032	0.53	0.53	32.32	Measured discharge
374.2	19.10	.22	.028	.59	.59	33.38	Measured discharge
374.2	76.20	.35	.023	.97	.96	40.03	Measured discharge
374.2	170.00	.39	.028	1.51	1.48	42.15	Estimated bankfull discharge

Table 12. Hydraulic variables simulated by the HEC-RAS model for Charles River at Medway, Massachusetts —*Continued*

River station	Discharge (ft^3/s)	Froude No.	Manning's coefficient	Average depth (ft)	Hydraulic radius (ft)	Total wetted perimeter (ft)	Notes
580.9	8.20	.08	.035	.45	0.44	63.21	Measured discharge
580.9	10.50	.08	.032	.49	.48	66.73	Measured discharge
580.9	12.60	.09	.030	.52	.51	69.03	Measured discharge
580.9	14.20	.09	.028	.54	.53	70.28	Measured discharge
580.9	19.10	.10	.024	.59	.58	73.82	Measured discharge
580.9	76.20	.12	.063	1.07	1.04	103.27	Measured discharge
580.9	170.00	.13	.055	1.71	1.65	104.79	Estimated bankfull discharge
641.1	8.20	.43	.500	.34	.33	17.09	Measured discharge
641.1	10.50	.44	.500	.38	.37	18.04	Measured discharge
641.1	12.60	.46	.500	.41	.40	18.88	Measured discharge
641.1	14.20	.49	.500	.41	.41	19.68	Measured discharge
641.1	19.10	.58	.500	.38	.37	25.68	Measured discharge
641.1	76.20	.27	.088	.82	.81	67.54	Measured discharge
641.1	170.00	.27	.050	1.37	1.35	70.03	Estimated bankfull discharge
691.6	8.20	.25	.047	.22	.22	54.84	Measured discharge
691.6	10.50	.25	.048	.27	.26	55.26	Measured discharge
691.6	12.60	.24	.049	.30	.30	55.64	Measured discharge
691.6	14.20	.24	.050	.33	.32	55.90	Measured discharge
691.6	19.10	.27	.043	.37	.36	56.32	Measured discharge
691.6	76.20	.34	.034	.77	.76	59.51	Measured discharge
691.6	170.00	.34	.050	1.27	1.24	62.47	Estimated bankfull discharge
1,284	8.20	.09	.060	.53	.52	43.25	Measured discharge
1,284	10.50	.09	.060	.58	.58	44.45	Measured discharge
1,284	12.60	.10	.060	.63	.63	45.39	Measured discharge
1,284	14.20	.10	.060	.67	.66	46.12	Measured discharge
1,284	19.10	.11	.060	.72	.72	49.72	Measured discharge
1,284	76.20	.17	.060	1.27	1.26	57.07	Measured discharge
1,284	170.00	.17	.060	2.07	2.02	59.04	Estimated bankfull discharge
1,466.3	8.20	.91	.040	.17	.17	21.84	Measured discharge
1,466.3	10.50	1.01	.040	.19	.19	22.15	Measured discharge
1,466.3	12.60	1.01	.040	.21	.21	22.56	Measured discharge
1,466.3	14.20	1.00	.040	.23	.23	22.91	Measured discharge
1,466.3	19.10	1.01	0.040	0.27	0.27	24.01	Measured discharge
1,466.3	76.20	.42	.070	.80	.80	45.07	Measured discharge
1,466.3	170.00	.35	.070	1.43	1.41	49.82	Estimated bankfull discharge

Table 12. Hydraulic variables simulated by the HEC-RAS model for Charles River at Medway, Massachusetts —*Continued*

River station	Discharge (ft^3/s)	Froude No.	Manning's coefficient	Average depth (ft)	Hydraulic radius (ft)	Total wetted perimeter (ft)	Notes
1,481.8	8.20	.36	.070	.26	.26	30.31	Measured discharge
1,481.8	10.50	.38	.064	.29	.29	31.07	Measured discharge
1,481.8	12.60	.40	.060	.31	.31	32.17	Measured discharge
1,481.8	14.20	.42	.057	.32	.32	33.13	Measured discharge
1,481.8	19.10	.46	.051	.35	.35	35.01	Measured discharge
1,481.8	76.20	.47	.046	.73	.73	45.43	Measured discharge
1,481.8	170.00	.39	.050	1.26	1.25	53.64	Estimated bankfull discharge
1,498.9	8.20	.24	.110	.32	.31	34.85	Measured discharge
1,498.9	10.50	.28	.090	.33	.32	35.31	Measured discharge
1,498.9	12.60	.32	.075	.34	.33	35.65	Measured discharge
1,498.9	14.20	.35	.067	.34	.34	35.85	Measured discharge
1,498.9	19.10	.40	.059	.38	.37	37.14	Measured discharge
1,498.9	76.20	.45	.065	.69	.67	52.13	Measured discharge
1,498.9	170.00	.40	.065	1.18	1.15	59.31	Estimated bankfull discharge